Debris-flow early warning system at regional scale using weather radar and susceptibility mapping

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Abstract

Risk mitigation for debris flows at regional scale is a challenge. Early warning systems are helpful in depicting the time and the location of future debris flows so that emergency responders can act in advance before the disaster takes place. Herein we present a prototype real-time regional early warning system for rainfall induced shallow landslides and debris flows for the region of Catalonia (northeastern Spain). The model issues a warning level combining susceptibility information and real-time rainfall triggering conditions obtained from weather radar observations and forecasts. Susceptibility maps have been derived using a fuzzy-logic approach and two input variables, terrain slope and land cover. These maps have been obtained using (i) grid cells of different resolutions, and (ii) physical catchments (of first order) as terrain units. Although high resolution grid-cell maps show a more accurate representation of susceptibility over the region, maps based on catchments are more intuitive and better characterize the area affected by future debris flows. Rainfall triggering conditions are assessed by means of probabilistic intensity-duration thresholds obtained from literature. Finally, we have validated the early warning system and tested its performance for some important events from the last ten years that were either monitored in specific catchments, or were reported in unmonitored catchments. In general, the system has been able to satisfactorily forecast the time of occurrence of most of the analyzed past debris-flow events.

Keywords: Debris flow; Early Warning System, Susceptibility map; Rainfall thresholds; Weather radar; Catalonia

1. Introduction

Debris flows represent an important hazard in mountainous regions and can cause substantial economic and human losses. Although debris flows are not as widely reported in Catalonia (northeastern Spain) as in other regions, they still represent a significant hazard (Portilla et al., 2010; Raïmat et al., 2010; Abancó, 2013; Palau et al., 2017).

Rainfall is the most important debris-flow trigger in Catalonia. Intense rainfall events are expected to increase in frequency due to climate change (Gariano and Guzzetti, 2016). In such a context, strategies to reduce the risk by increasing awareness, and preparedness of communities living at areas that may be affected must be developed (UNISDR, 2015; Alcántara-Ayala et al., 2017). Early warning systems help us anticipate the risk prior to the event, in order that emergency strategies could be adopted in advance.

The majority of early warning systems focus on rainfall induced shallow landslides and debris flows on natural slopes (Aleotti, 2004; Chen and Lee, 2004; Baum and Godt, 2010). Most of them use rainfall inputs obtained from rain gage data. However, the density and temporal resolution of rain gage networks is usually low and landslide triggering rainfalls tend to be underestimated (Marra et al., 2014). The main advantage of radar data is its high temporal and spatial resolution (of the order of one kilometer and up to five minutes). Only in few early warning systems radar measurements have been adopted instead; e.g. Japan (Osanai et al., 2010), Southern California (NOAA-USGS Debris Flow Task Force, 2005) and the Pyrenees (Berenguer et al., 2015).

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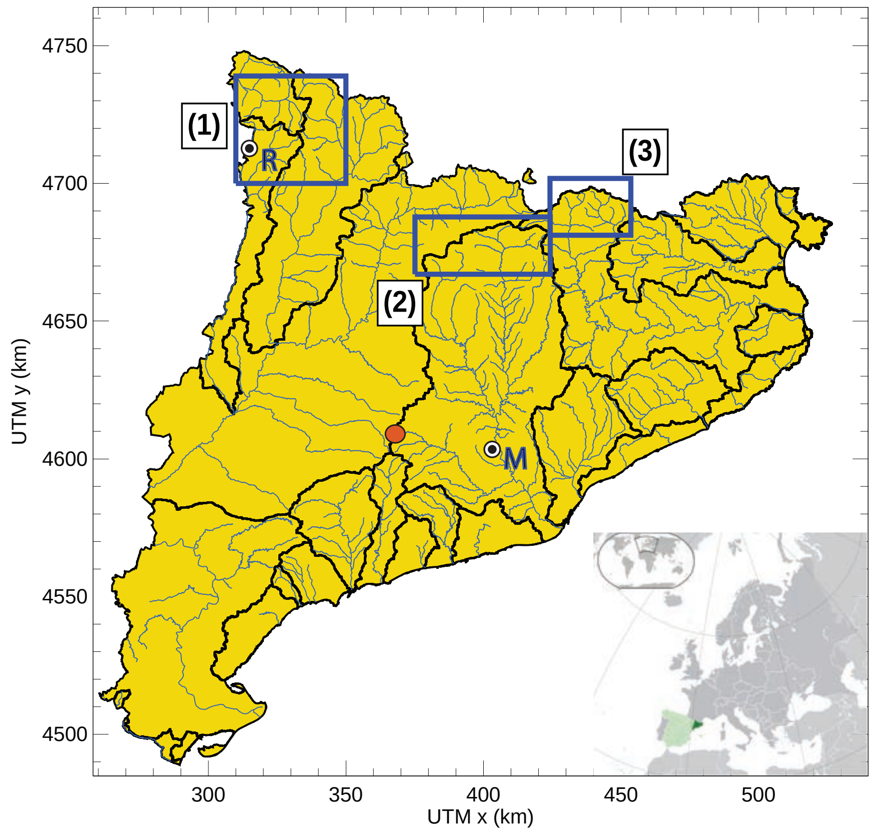

Fig. 1. Overview map of the Catalonia region. The Rebaixader Catchment (R) and Montserrat (M) locations are marked with a concentric black circle. The orange circle represents the location of the radar. The zones of the inventories used for the susceptibility maps are delimited by the blue rectangles.

The terrain predisposing factors can be considered by means of landslide susceptibility maps. The majority of them are raster maps (Carrara et al., 2007; Kirschbaum et al., 2016; Bee et al., 2018; Wilde et al., 2018), but some use other terrain units as hydrological catchments (Cannon et al., 2004; Carrara et al., 2007; Chevalier et al., 2013; Hürlimann et al., 2016; Krøgli et al., 2017). Choosing the most appropriate susceptibility terrain unit requires considering several factors and is not always trivial.

The main aim of this work is to present an updated version of the early warning system of Berenguer et al., (2015) for the Catalan Pyrenees. The new version of the early warning system covers the entire Catalonia region, uses an updated susceptibility map and a new approach to define the critical rainfall. The effect of using different terrain map units for the susceptibility classification is also introduced. Finally, the early warning system has been run for the summer season of 2010 (April to October) using radar Quantitative Precipitation Estimates (QPE) and validated for some recorded events occurred in specific catchments.

2. Methodology

The prototype early warning system presented herein uses information on debris-flow susceptibility and rainfall observations. These two inputs are combined in real-time to obtain a qualitative warning level (very low, low, moderate or high).

2.1. Susceptibility assessment

In this work, two terrain features were seen as the most important in order to derive the susceptibility map of Catalonia: slope and land cover. To calibrate and validate the susceptibility model, information on past debris-flow and shallow landslide events contained in the inventories of three zones of the Catalan Pyrenees is introduced. Slope accounts for the topography of the terrain. Land cover accounts for the terrain resistance parameters. Additionally, we attempted to use the geology map to provide some information about the surface deposits, but this information showed no clear skill in characterizing landslide susceptibility.

The susceptibility class is calculated for each of the terrain units using a fuzzy logic classifier (Mendel, 1995). The classifier requires membership functions for each variable, that were obtained based on expert criteria. Then, a weight is assigned to each variable. In our case, we have defined four classes: “very low”,” low”,” moderate” and “high” susceptibility. Therefore, for each variable there are four membership functions, one for each susceptibility class. The membership degree to each susceptibility class is calculated for each of the terrain units as the weighted average of the membership degrees for the two variables. The susceptibility class having higher membership degree is assigned to each terrain unit.

The last step of the susceptibility assessment is the validation of the resulting susceptibility maps. Receiver Operating Characteristics (ROC) curves have been calculated (Fawcett, 2006), and the area under the curve (AUC) is the metrics used to assess the model performance.

2.2. Analysis of triggering rainfalls

For the purpose of this work, rainfall inputs are obtained from the observations of the CDV C-band radar of the Meteorological Service of Catalonia (SMC) with the chain of algorithms of the Integrated Tool for Hydrometeorological Forecasting (EHIMI, Corral et al., 2009). This tool includes the correction of the beam-blockage effect, ground clutter elimination, identification of the type of precipitation, extrapolation of elevated reflectivity measurements to surface and conversion of reflectivity to rain-rate. The rainfall products used here consist of real-time 30-min radar rainfall accumulations with a spatial resolution of one kilometer. Additionally, radar-based nowcasts (Berenguer et al., 2011) could be included to increase the lead-time.

To assess if a given rainfall event has the potential of triggering a debris flow, the global probabilistic rainfall intensity-duration percentile thresholds obtained by (Guzzetti et al., 2008) have been adapted. The thresholds represent the percentile of past shallow landslides and debris flows triggered by a given rainfall intensity and duration. Using them, four rainfall hazard levels have been defined: “very low”, “low”, “moderate” and “high” (see Figure 2). If a set of more local rainfall thresholds is available, they could be easily adapted in the LEWS.

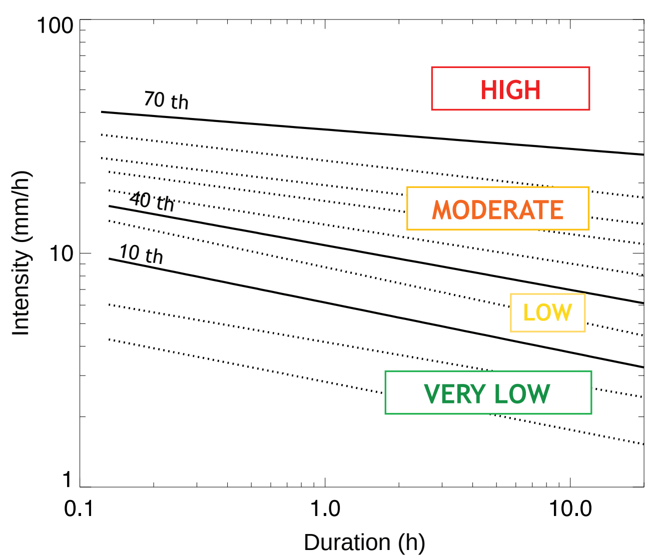

Fig. 2. Rainfall intensity-duration thresholds adapted from Guzzetti et al. (2008) and selected rainfall hazard levels. The continuous lines represent the 10th, 40th and 70th percentiles of rainfall that were selected as thresholds.

2.3. Combination of susceptibility and rainfall: Issuing a warning level

In the current configuration, susceptibility information is a static input in the early warning system, while the radar-based rainfall estimates are updated every 30 minutes.

The combination of the four susceptibility classes and the four rainfall hazard classes is done by means of a warning level matrix (Figure 3). The columns of the warning level matrix represent the susceptibility and the rows represent the rainfall hazard. The combination of each susceptibility class with each rainfall hazard class results in a warning level, which again is of four classes: “very low”, “low”, “moderate” and “high”.

The final result is presented in the form of a warning level map assessing the possibility of having a debris flow in each terrain unit for every time-step.

Rainfall hazard level	Susceptibility Very Low	Susceptibility Low	Susceptibility Moderate	Susceptibility High
Rain Very Low	VL	VL	VL	L
Rain Low	VL	L	L	M
Rain Moderate	VL	L	M	H
Rain High	L	M	H	H

Fig. 3. Warning level matrix. Rows represent rainfall hazard level, columns represent susceptibility class. VL states for very low, L for low, M for moderate and H for high warning level.

3. Analyzing the influence of the terrain unit

A terrain unit is a portion of the terrain that can be distinguished from the terrain units around it because of its properties (Hansen, 1984). It should maximize internal homogeneity and enhance heterogeneity between different terrain units (Guzzetti et al., 2005). Choosing an appropriate terrain unit requires considering the studied phenomena, the available datasets, the resolution, the quality of the results and the final purpose of the susceptibility map among other factors.

As part of this work, we are studying the applicability of the early warning system to different terrain units. Herein we will examine the possible advantages and limitations of using (i) first order catchments (Strahler, 1957), (ii) and 30 m resolution grid-cells.

Since debris flows are transported along channels, the initiation, transportation and deposition zones coincide with the area defined by hydrological catchments. The majority of debris-flow events were recorded in first order basins. Such catchments located at the headwaters are usually steeper and generally have higher susceptibility than higher order catchments. For this reason, we have set up the early warning system using a susceptibility map based on first order basins.

Both maps shown in Figure 6 have approximately the same percentage of moderate and high warning level terrain units: 38% and 58% respectively in the case of first order basins, and 38% and 52% in the case of 30 m resolution grid-cells. However, the number of terrain units classified as very low and low susceptibility is somewhat different. 8% of the pixel-based map is classified as very low and 2 % as low susceptibility, whereas the first order basins map has no terrain unit with very low susceptibility and classifies only a 4% of terrain units as having low susceptibility. As a result, the number of warnings issued when using the basin-based susceptibility map will probably be higher than when using the pixel-based susceptibility map.

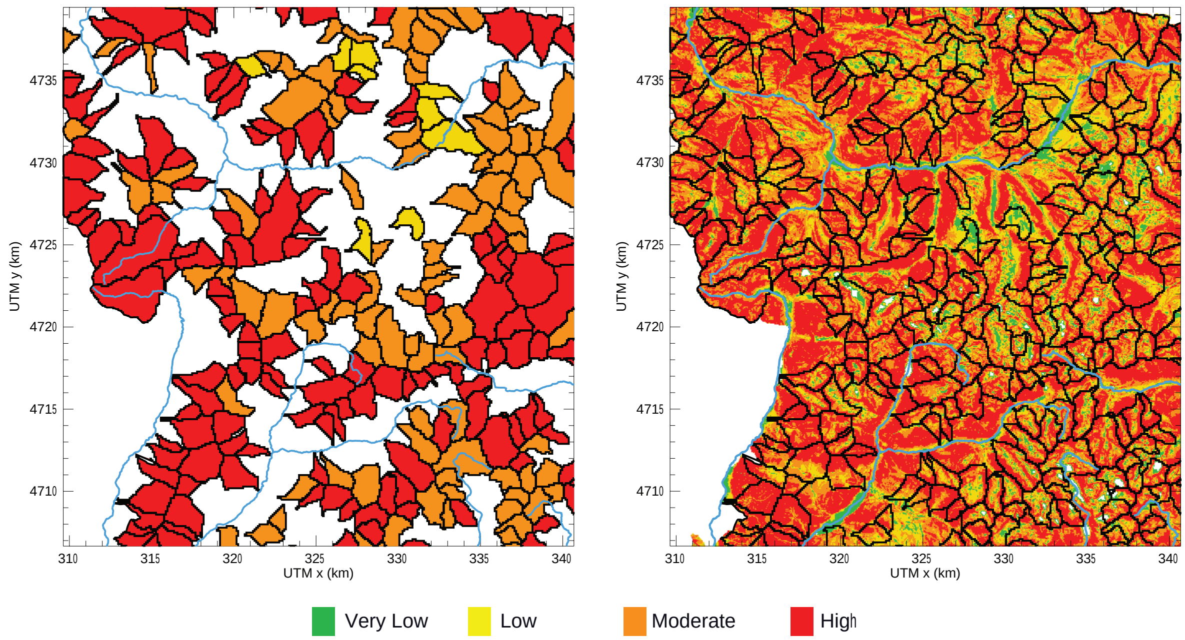

Fig. 6. Preliminary results of susceptibility mapping. a) Map based on first order basins for the NW-Catalonia region, b) map based on 30 m resolution grid cells for the same region.

Maps based on grid-cells have the advantage of covering the entire analysis domain but unlike first order basins lack of physical meaning. For this reason, early warning system results will be easier to interpret when using the susceptibility map based on first order basins.

Another important aspect when thinking on the implementation of the susceptibility map into the proposed real-time early warning system is the required computational time required to compute a time-step over the region of Catalonia. A priori it seems that the 30 m resolution grid-cell configuration will be more computationally demanding than the configuration based on first order catchments.

4. Results

First, we have generated a susceptibility map for the Catalonia region based on first-order basins and run the prototype early warning system for a period of seven months in 2010. The early warning system outputs have been checked for recorded events in monitored and unmonitored catchments. All the recorded events are associated with a moderate or high warning levels, and coincide with intense rainfall episodes.

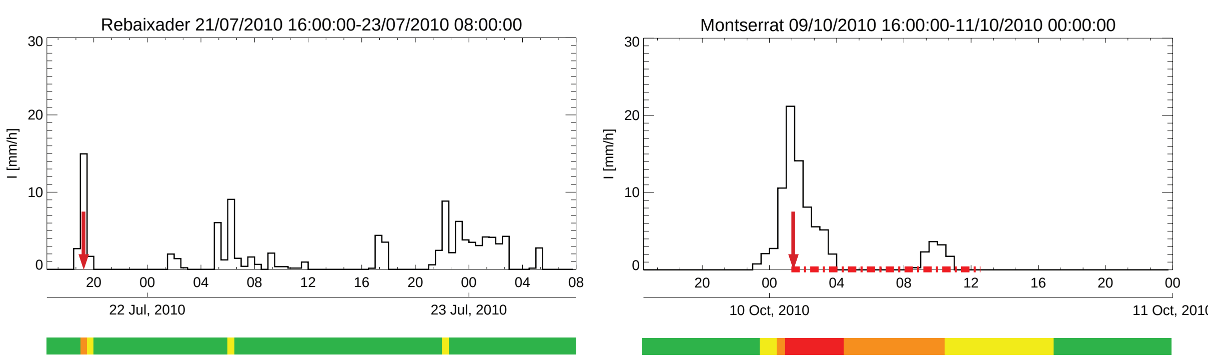

Fig. 4. Output of the early warning system for a debris-flood event in the Rebaixader catchment and a debris-flow event in Montserrat. The black line shows the evolution of the rainfall intensity in the catchment, and the color bar indicates the warning level diagnosed with the warning system. Green, yellow, orange and red correspond, respectively, to “very low”, “low”, “moderate” and “high” warning level. The red arrows represent the time the Rebaixader monitoring station recorded the debris flow and when the event was reported at Montserrat. The discontinuous red line represents the period of time road and railway remained closed.

This is the case for the events shown in Figure 4. The first case corresponds to the event that occurred on 21 July 2010 at the Rebaixader catchment. A debris-flow monitoring system has been running in this catchment since 2009 (Hürlimann et al., 2014) and recorded a debris-flood event at 19:05. The early warning system issued a moderate warning level for the same time. Figure 4 (right) shows the case of the 09-10 October 2010 at the Montserrat basin. In this case the exact time of the debris-flow event is unknown. However, a road and a railway were blocked by a debris flow and remained closed on 10 October 2010 from approximately 01:00 to 12:00, coinciding with the time when the system issues moderate and high warning levels.

Many debris-flow events happen in remote areas and are not recorded. Thus, one of the challenges in the evaluation of the early warning system performance is the correct determination of the total number of false alarms and misses. The number of days with moderate and high warning level has been counted for every first order basin (Figure 5). Results for monitored and unmonitored catchments where debris flows have been reported are promising. Four events were recorded at the Rebaixader monitoring site, and the prototype LEWS issued a total of five days with moderate or high warning. However, in Montserrat only one event was reported, but seven days presented a moderate or high warning.

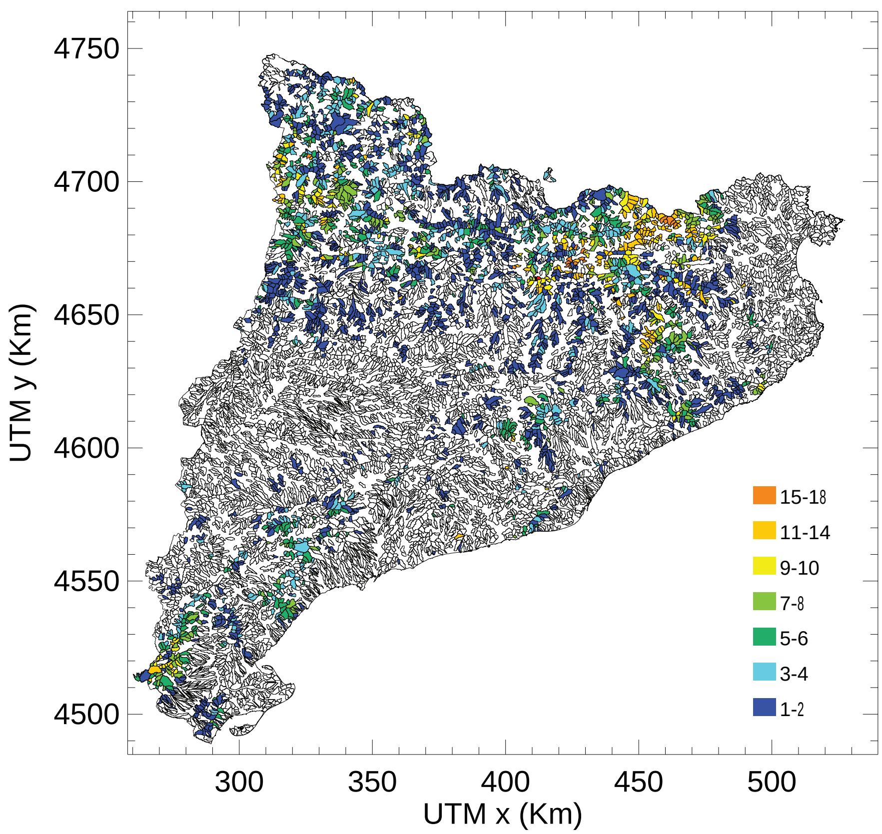

Fig. 5. Number of days with moderate or high warning level for each of the first order catchments between April and October 2010.

5. Conclusions

Early warning systems constitute a useful tool for the mitigation of debris-flow and debris-flood impacts. The methodology proposed herein presents a regional scale early warning system. The presented early warning model makes use of only two input parameters. A susceptibility map accounting for the terrain predisposing factors, and the triggering rainfall that is assessed by means of weather radar observations and probabilistic rainfall thresholds. The output of the early warning system is a warning level (very low, low, moderate and high) that is computed for each terrain unit by means of a warning level matrix.

We have implemented the early warning system for the Catalonia region using a susceptibility map based on first order basins and ran it for a seven-month period in 2010. An important challenge in this domain is the correct determination of the number of false alarms and misses. Most debris-flow events happen in remote areas and many are unreported. Therefore, the evaluation of the performance of the early warning system is challenging.

The influence of terrain map units on the early warning system performance is an interesting topic. We have presented preliminary results comparing susceptibility maps based on first order basins and 30 m resolution grid-cells. On the one hand, the interpretation of the early warning system seems easier using susceptibility maps based on first order basins. On the other hand, the analysis area is not completely covered. Another drawback is that considering the terrain land cover variability is difficult. As a result, the susceptibility tends to be higher. The implementation of the susceptibility map of 30 m resolution pixels into the early warning system would cover the entire domain, account for land cover variability and provably issue higher resolution warnings. However, it would complicate the interpretation of the outputs and require more computational resources. Although using first order basins may seem better, choosing the best mapping unit requires implementing the two susceptibility maps into the early warning system and consider the performance of both configurations.

Finally, in the context of an Early Warning System, extending the lead time is fundamental to enable efficient emergency management. In real time, it will thus be advisable to extend the series of radar observations with high-resolution rainfall forecasts (such as radar-based rainfall nowcasts).

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